"Theoretical ideas of the investigation of SRC in high energy processes off nuclei"

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Introduction

SRC were observed in the variety of high energy processes off nuclei kinematically forbidden for the scattering off stationary nucleon target:

$$e(\mu) + A \to e(\mu) + A$$

in near threshold and DIS $x \geq 1$ regimes.

$$\nu(\bar{\nu}) + A \to \mu(\bar{\mu}) + A$$

in DIS $x \geq 1$ regime

$$e(\nu) + A \to e'(\mu) + X + backward\ p(n)$$

$$p + A \to p(high\ p_t) + X + backward\ N$$

and probably observed in the another, even larger group of data with backward hadron carrying fraction of nucleus momentum x_F

$$3 > x_F \geq 1$$

$$p(pion, \gamma, \nu, light\ nuclei) + A \to X + backward\ N(pi)$$

One of advantages of high energy processes is that high energy $100 MeV$ ***projectile transfers to a nucleus energy significantly larger than the scale characterizing short range nucleon correlations in nuclei- analogue of microscope. Dominance of spectators and significant difference in energies and momenta of knocked down nucleon and spectator allows to identify experimentally yield of pair nucleon correlation and predict many features of the yield of short range inter nucleon correlations in nuclei (SRC) in mostly model independent way. Note that the research is able to supply direct information on nucleon momentum distribution but concept of SRC in non relativistic nuclear theory is coordinate space concept.*** Fourie transform of smooth functions in coordinate space and of coordinate space functions with singularity produces different dependence on nucleon momentum. Within mean field approximation

$$n_A(k) \propto exp - (k^2/k_0^2)$$

But potential of inter nucleon interaction contains core. So at the inter nucleon distances close to nuclear core coordinate space wave is changing rapidly. The contribution of SRC produces functions of the type or more complicated which is decreasing with k significantly more slowly than mean field approximation- $n_A(k) \propto (1/k^4)$ and win at sufficiently large k.

Within the non relativistic approximation to nuclear wfs these processes are described in terms of different functions:

i.nucleon density describes nucleon motion within nucleus and nucleus electromagnetic form factors.

$$n(k) = \int \psi^2(k, k_i) P_{prod} d^3 k_i$$

ii. Spectral function describes scattering processes off nucleon target which are on mass shell.

$$S(k) =< \psi_A | a^+(k) \delta(E - H) | a_(k) | \psi_A >$$

iii. decay function describing decay of rest of nuclear system when one nucleon is removed . We introduce above annihilation and production operators a(k), $a^+(k)$
This fact is often ignored in the literature and so far there are no numerical calculations of decay functions. Nevertheless conclusions based on the analysis of experimental data for different functions are close. This is consequence of remarkable property of exact sum rules and differential equations where mean field and SRC have different dependence o nucleon momentum and therefore distinguishable.

m_π $E_0 \approx 1GeV$

With increase of collision energies scale of hadronic phenomena is increasing also from the scale characteristic for nuclear phenomena - $r_{NN} \approx 1/\sqrt{(1/2m_N E_0)}$ approximately for soft QCD processes and further increasing with energy and to significantly larger scale for hard QCD processes like DIS,high p_t phenomena etc. This property guarantees feasibility to resolve nuclear structure up to .

Data agree with the probability of high momentum component to be beyond the Fermi surface around 20% for heavy nuclei and with the distinctive properties of pair nucleon correlations expected within the standard nuclear theory: weakly dependent on projectile and nucleus target dependence on nucleon momentum similar to that for the deuteron target, observed probability of p,n correlation is significantly larger than p,p(n,n) one , dominance of D wave within the pair nucleon correlation etc. cf. talks at this conference. (cf.talk of E.Piasetsky)

Specific of space-time evolution of high energy processes .

Theory of high energy processes should take into account general properties of high energy processes which are absent in the low energy nuclear physics :

i. high energy processes occur at light cone: $(t^2 - r^2)E_o^2 \leq 1$ ***. time t=z . Here z is the distance in the collision plane . Thus time=distance and t increases lineary with collision energy -follows from Lorentz slowing down of interaction.***

ii. coherence of high energy processes which follows at high energies from the significant cross section of inelastic diffractive phenomena. (Observed recently by ATLAS at LHC.)

iii. Calculations of amplitudes for high energy processes in terms of non relativistic nuclear wfs should be understood as non relativistic limit of amplitudes calculated in terms of lc wfs of nuclei . Ignoring this property complicates analysis of data and leads to significant fake effects violating probability conservation within this approach. Special relativistic effects should exist also. I will explain this important point in the talk.

One of consequences of such a research will be feasibility to control uncertainties of calculations related to SRC.

So major directions of research:

- ☛ Systematic implementation of light cone dynamics and coherence of high energy processes , exact conservation laws such as energy-momentum conservation=electric,baryon charge conservation, conservation of probability, establishment of the region of applicability of light cone quantum mechanics of deuteron and nuclei.

- ☛ Observation of special relativistic effects in the nucleon momentum distribution within SRC-will be discussed briefly in the talk.

- ☛ Establishing the role and properties of triple nucleon correlations which should have more significant role in the inner core of neutron stars.

- ☛ Role of nonnucleon degrees of freedom in nucleus wf-nucleon excitations in nuclei as evidence of of the role of kneading of quarks and gluons between adjacent nucleons-problem of dibaryon resonanses(?)..

Outline of the talk

- ☛ Outline of significant fake effects arising due to ignoring in the non relativistic theory production by projectile of pairs from vacuum which is actually significant (probably dominant) effect. We explain that to avoid fake effects in a wide kinematical region where dominant degrees of freedom in nuclear wf are nucleons standard nuclear theory should be understood as non relativistic limit of light cone mechanics of nuclei.

- ☛ Light cone mechanics of deuteron. New effect-angular distribution of spectators with relativistic momenta. Estimate of the region of applicability of dominance of nucleon degrees of freedom.

- ☛ Light cone dynamics of nuclei. Master equation. Spectral and decay functions . Decomposition of high momentum tail of nuclear wf over the contributions of SR correlations and scaling laws in $x \geq 1 \quad e\ A \rightarrow e\ A\ processes$

- ☛ Conclusions

Fake violation of probability conservation in the straightforward applications of non relativistic nuclear theory to high energy processes.

- Let us calculate cross section of DIS off deuteron target :

$$\sigma(\gamma + d \to X) = \int \psi^2(k) d^3k \sum \sigma(\gamma + N \to X)$$

$$\int \psi^2(k) d^3k = 1$$

These equations taken together contradict to exact momentum ,conserved charges (electric,baryon...) sum rules . This is because in the total cross section integration over momentum k is restricted by positiveness of invariant mass in the cross section of photon -nucleon collision. The contradiction is that in the normalization condition all nucleon momenta are allowed. Theoretical analysis found that second equation is incorrect if relativistic nucleon motion is taken into account. Correct normalization of wave follows from the evaluation of matrix element of conserved current at zero momentum transfer:

$$< d|j_0|d >= 1$$

To visualize origin of fake effects let us consider production of spectator with momentum k off deuteron : $a + d \to X + N$ .The ratio of the invariant energy released in aN scattering to total invariant energy $\alpha = (m_d - k_3 - \sqrt{m^2 + k^2} \geq 0$

So for $k_t = 0$ $k \leq (m_d^2 - m_N^2)/2m_d$

- Variable α (Feynman x) has straightforward interpretation : this is fraction of light cone momentum of deuteron carried by spectator nucleon . So within QCD : $0 \leq \alpha \leq 1$ This variable being Lorentz invariant in t, z plane is convenient for the theoretical description of the yield of spectators in both nucleus rest frame and infinite momentum frame. Pair nucleon correlation in wf of lc mechanics neglecting its c.m. motion has the form :

$$\alpha_1 + \alpha_2 = 1; k_{1,t} + k_{2,t} = 0$$

Instead of $k_{3,1} + k_{3,2} = 0$

Taking the residue within the triangle diagrams over light cone variable $k_0 + k_3$ produces the same Θ function as in the cross section .

Origin of the puzzle with normalization condition is in the lack in the non relativistic nuclear theory of production of pairs from the vacuum. Light cone (infinite frame approach) allows to account for pair production from vacuum which actually dominates in the amplitudes of high energy processes . Thus one should calculate amplitudes of high energy processes in terms of light cone wave functions of nuclei and then to make non relativistic approximation and obtain in the domain $k/m \ll 1$ formulae close to that familiar from non relativistic nuclear theory with some relativistic effects as correction.

- Numerical calculation of G.West found that account of discussed above mismatch between the formulae for cross section and normalization of nuclear wf leads to the significant correction to the structure functions of nuclei which is numerically comparable with the value Glauber shadowing for $\sigma_{tot}(\pi d)$. Experimentalists of SLAC used this correction in the extraction of nucleon structure functions from ed scattering but reanalyzed data later to remove this correction.

Another example of fake effects is supplied by the models of the EMC effect which violate exact momentum and/or baryon sum rules derived in QCD for structure functions of nuclei.

Master equation of lc dynamics for deuteron

- Propagator describing system of two uninteracting particles with total mass M: $$\frac{1}{M^2-4m^2-k_t^2/\alpha(1-\alpha)}$$

$\alpha = p_{i_+}/P_+$ and k_t is relative transverse momentum.

where $P_+ = P_0 + P_3$ is total momentum of the system.

Mass of intermediate state is given by the formulae:

$$M_{int}^2 = 4(m^2+\kappa^2)$$

Two body phase volume - $d\tau_2$

$$\delta(\alpha_1+\alpha_2)\delta(k_{1t}+k_{2t})(d\alpha_1/2\alpha_1)(d\alpha_2/2\alpha_2)d^2k_{1t}d^2k_2t/(2\pi)^3$$

If $\alpha = 1/2(1+\kappa_3/\sqrt(\kappa^2+m^2)$

phase volume obtains familiar form:

$$d\tau_2 = \frac{d^3\kappa/}{\sqrt(\kappa^2+m^2)4(2\pi)^3}$$

The form of space-time evolution time is fixed in the approximation when number of particles is conserved. This allows to derive master equation for lc deuteron wf .Angular momentum constraint is derived as the consequence of necessity to reproduce on mass shell amplitude. Thus equation for off shell l.c. amplitude T obtains the form:

$$T(\kappa_i,\kappa_f) = V(k_i,k_f) + \int V(\kappa_i,\kappa')(d^3\kappa'/\sqrt(\kappa'^2+m^2))(1/(1/2\pi)^3T(\kappa',\kappa_f)/4(\kappa^2-\kappa_f^2)$$

- Normalization of wave function should be derived from the evaluation of matrix element of conserved current: electric charge, baryon charge, energy-momentum tensor. In the non relativistic approximation this equation is reduced to Lippman-Schwinger equation of non relativistic quantum mechanics. The main new relativistic effect expected for high energy prκocesses for the yield of spectators is non trivial difference between measured momentum of spectator -k and argument of wave function .This implies specific dependence on the angle between momentum of projectile virtual photon and spectator momentum (for large nucleon-spectator momenta) which is different from that naive expectations based on the non relativistic theory.

Estimate of kinematical domain where nucleon degrees of freedom dominate in the wave function of nucleus.   .

Dominant pair correlation has isospin 0 and L=0. So we need to consider thresholds of heavy resonance production. This estimate is natural within string approach.

i. 2 Δ state

$$k \leq \sqrt{(M^2_{Delta} - m^2_N)} \approx 0.7 GeV$$

ii. NN^* state

$$\kappa \leq \sqrt{(1/4)(m_N + m^*_N)^2 - m^2_N} \approx 0.7 GeV$$

- Large value of thresholds is relevant for the existence of nuclear physics-phenomenon of spontaneously broken chiral symmetry. Presence of non nucleon degrees of freedom should play important role in the evaluation of the EMC effect-cf.M.Strikman talk

Existence of constraints on the region of applicability of LCM imply that matrix elements of some operators can not be calculated in terms of nucleon degrees of freedom . One example is the transverse component of electromagnetic

current. So calculations should explore operators with minimal contribution

of production of $N\bar{N}$ pairs off the vacuum.

Description of electromagnetic form factors of deuteron requires approximately the same high momentum component as for the description of other processes in the kinematical region forbidden for the scattering off stationary nucleon.

LC mechanics of nucleus.

- Space-time evolution describing nuclear physics is the same as in LCM in the approximation when the number of degrees of freedom is fixed. Simply "potentials" (diagrams containing no nucleon intermediate states) are different.

- So equation for the off mass shell amplitude :

$$T = V + V * P * T$$

- Potential V contains any inter nucleon interaction. Propagator

- $$P^{-1} = 2P(E - \sum \sqrt(m^2 + (\alpha_i P)^2 + k_{i,t}^2) = M^2 - \sum (m^2 + k_{ti}^2)/alpha_i)$$

If to introduce variables

$$\alpha_i = A \frac{\sqrt(m^2 + \kappa_i^2 - \kappa_{3,i})}{\sum \sqrt(m^2 + \kappa_i^2)} =$$

$$P^{-1} = M^2 - \sum (m^2 + \kappa_i^2)$$

Difficult problem is to account for the conservation of angular momentum=rotational invariance. It follows from Lorentz invariance of on mass shell amplitudes. This allows to establish properties of "potential" V up to numerically small corrections

- Having master equation allows to build correlation having at small nucleon momenta correct non relativistic form. Thus framework for numerical calculations is formulated.
- This allows to build light-cone-density matrix $\rho_A(\alpha, p_t)$, Spectral function $S_A(\alpha, p_t, p_{rec})$,decay function.

l This framework allows to account for the energy-momentum conservation-to separate scattering off several nucleons, to implement all exact conservation laws like electric charge, baryon charge, to avoid fake effects.

- This concept allows to evaluate the role of many nucleon correlations.

Since nucleus is diluted system one may to decompose correlation functions over contributions of few nucleon correlations

$$\rho_A^N = A\sum a_n \rho_n(\alpha, p_t)$$

$$a_n \approx (r_c/r_N N)^{3(n-1)}$$

$$\rho_2 = \rho_D = (2-\alpha)^m$$

$$\rho_n = (1-(1-(\alpha-1)/(n-1))^{(n-1)m+n-2}$$

- This few nucleon correlation model can be generalized to other densities.

This approach allows to probe relative role triple ,fourth correlations which probably key role in the inner core of neutron stars

- I omitted comparison with data since my aim is to explain basic ideas and methods of high energy nuclear physics, perspectives and unresolved problems. This subject is on the verge between nonrelativistic nuclear physics and QCD.